The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Detection Sensor for Flowing Particles in Micro Channel

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Abstract— **In this paper, we propose a sensor for detecting particles flowing in a micro channel fabricated with polydimethylsiloxane (PDMS) chip. A light source placed at one side of a micro channel irradiates the micro channel through plastic optical fibers (POF), and a detector placed at the opposite side of the micro channel receives light transmitted through the POF. Since this sensor simultaneously detects plural particles with a diameter of around 100 µm flowing in a micro channel, it can be implemented in automatic measurement systems of cells in desktop bio plant, on which automated embryonic cell manipulation is achieved using micro robotics technology.**

I. Introduction

Development in biotechnology in recent years has been remarkable. One such technology, cloning, is highly useful in many application fields such as regenerative medicine, drug discovery, and agriculture. However, cloning involves low productivity because that requires advanced and complicated procedures under a microscope executed only by skilled operator.

To improve its productivity, so-called desktop bio plant that enables automated embryonic cell manipulation (e.g., cutting, sorting, filtering, coupling, and fusing of cells each modularized and interconnected) using micro robotics technology has been studied [1]. However, there are no compact sensors adapted to automated embryonic cell manipulation. Previous proposed sensors with a light-scattered method [2], a light-intersecting method [3], and an electric resistance method are all medium or large sized, and designed not for detecting particles flowing in fluid but for measuring characteristics and properties of particles. Scattered light based sensors for measuring cells by irradiating with a laser through plastic optical fibers (POF) have been developed [4] [5]. A micro liquid injector that enables us to measure the reagent to a fixed amount has been proposed [6]. A sensing system to detect a cell in a micro channel has been developed, utilizing the light-intersecting method [7]. However, that is not designed to simultaneously detect plural cells.

In this paper, we propose a sensor for detecting particles flowing in a micro channel fabricated with polydimethylsiloxane (PDMS) chip using POF array. A light source and a detector are placed across a micro channel. A light source emits light onto the end of POF laid across the micro channel, and a detector receives light transmitted through the POF. Particles are detected by measuring changes in the amount of light output. POF has some advantages over silica fiber. It is more flexible, easier to handle, and lower in cost. We employ a red semiconductor laser with a wavelength of 650 nm for a light source, which is widely used in bio-related fields since it has no effect on cells. POF irradiated with a red laser exhibits low transmission losses. The features of this sensor include the followings.

1) Detects particles across the length of a micro channel
2) Simultaneously detects plural particles
3) Implemented on a micro PDMS chip
4) Easy to connect to a light source and a detector
5) Cost-effective and disposable

In this paper, we present experimental verification to evaluate the feasibility of the proposed sensor.

Manuscript received March 9, 2009.

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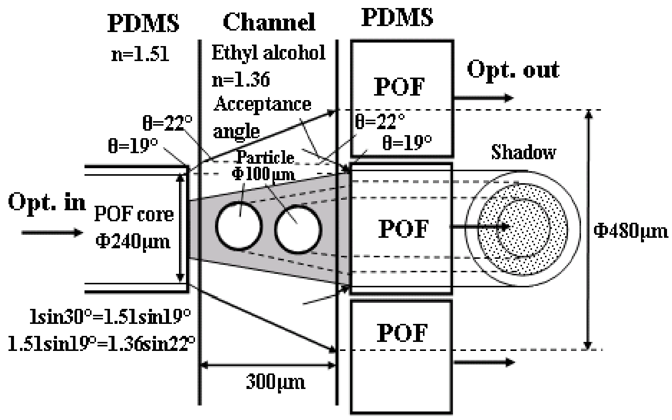
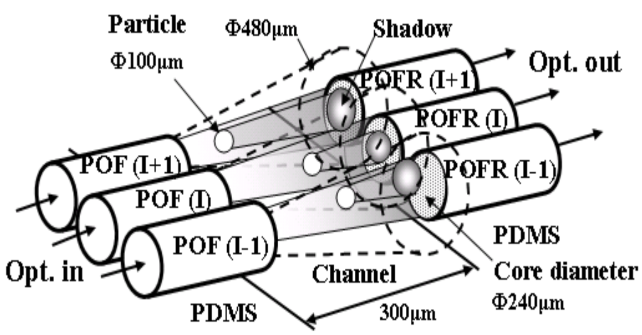
II. Proposal of Multifiber Array Sensor

A. Principle of sensing

The principle of the sensor is presented in Fig. 1. A light source placed at one side of a micro channel emits light onto the end of POF arranged across the micro channel, and a detector placed at the opposite side of the micro channel receives light transmitted through the POF. Particles in ethyl alcohol of dispersed catalyst are pumped into the micro channel. The light transmitted in POF passes through PDMS with a refractive index of 1.51 and a thin layer, and then through ethyl alcohol with a refractive index of 1.36. As a result, both incident and output angles of light transmitting in the micro channel yield 22°. When particles are in the optical spot, the amount of light output changes. The detector detects particles by measuring changes in the amount of light output. A 480 µm spot is formed when light passes through the 300 µm wide micro channel, while a 240 µm spot is allowed to enter the 240 µm diameter POF core. Particles in the spot block light and cast shadows, resulting in changes in the amount of light output. A 100 µm particle casts a shadow 18% of the POF core when the incident light is parallel to each other on the POF output. The shadow is larger as the light spreads. Transparent particles reduce light transmittance by 10% to approximately 90%. When transparent sphere particles are in the spot, the amount of light output decreases by > 1.8%, as they have similar optical properties to that of a

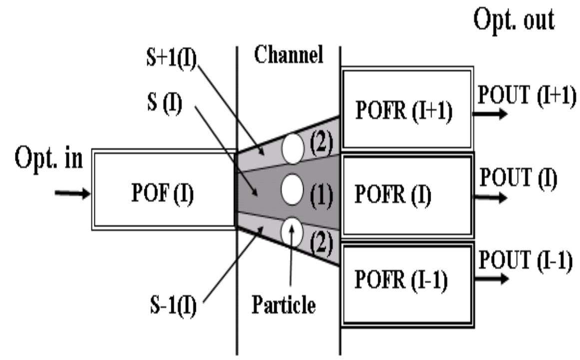


(a) Schematic diagram of light spot blocked with a particle in a micro channel

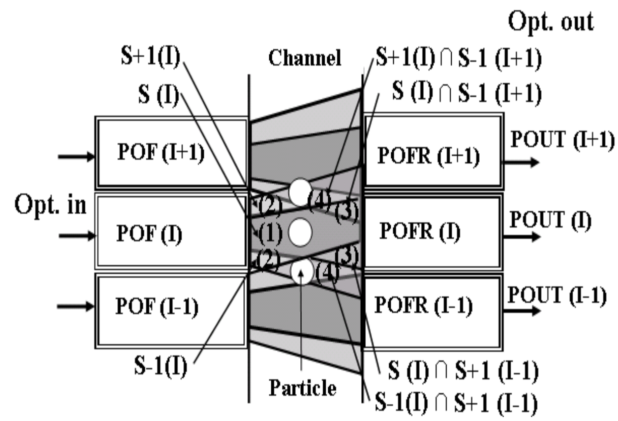


(b) 3D schematic diagram of light spot blocked with a particle in a micro channel

Fig. 1. Principle of a sensor



(a) Schematic diagram of transmitting light through one POF



(b) Schematic diagram of transmitting light through POF bundle

Fig. 2. Light beams in a micro channel

ball lens, so that they focus close to the surface leading to a wide spread of light. As actual particles are translucent, the amount of light output decreases further. The detector connected with POF detects particles by measuring changes in the amount of light output.

Fig. 2 (a) is a schematic diagram of irradiation onto one POF. When light is emitted on POF (I), POFR (I) on the opposite end of the micro channel forms optical spot S (I), and POFR (I ± 1) forms optical spot S ±1 (I).

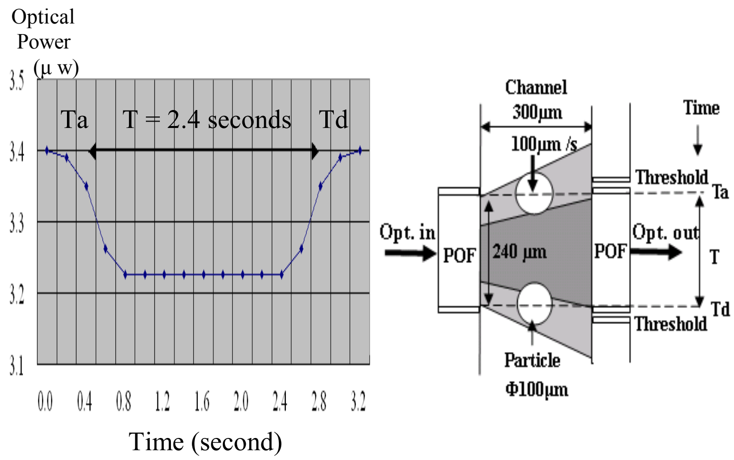
1) When a particle passes spot S (I), the amount of light output Pout (I) transmitted in POFR (I) changes.
2) When a particle passes spot S ± 1(I), the amount of light output Pout (I ± 1) transmitted in POFR (I ± 1) changes.

Fig. 2 (b) is a schematic diagram of irradiation onto POF in a bundle, where POFR (I) and POFR (I ± 1) receive light within the acceptance angle. With the POF bundle, the above-mentioned spot in 1) and 2) transforms into the spot presented below in 3) and 4).

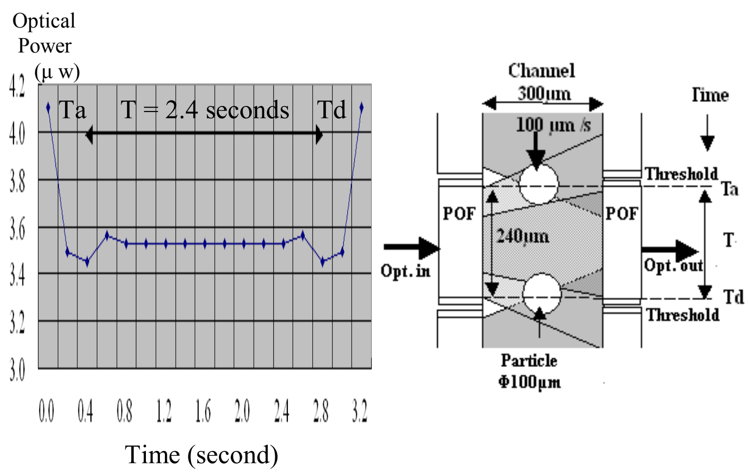
3) When a particle passes the spot where spot S (I) intersects spot S ∓ 1 (I ± 1), the amount of light output Pout (I) transmitted in POFR (I) changes.
4) When a particle passes the spot where spot S ± 1 (I) intersects spot S ∓ 1 (I ± 1), the amount of light output both of Pout (I) and Pout (I ± 1) change.

B. *Expected output model*

With sphere particles with 98 μm outer diameter flowing in a micro channel 100 μm per second, the expected amount of light output is shown in Fig. 3 in which the x axis represents time. We expect the amount of light output changes based on the ratio of a cross sectional area of a particle to a core area of POF. The transit time T when the center of a particle passes through the front of POF core is defined as Td-Ta. Ta represents an arrival time of the center of a particle at the POF core, and Td represents a departure time of that from the POF core. With one POF irradiated, the amount of light output is shown in Fig. 3 (a). The amount of light output decreases as a particle passes through the front of POF core on the transit time Td-Ta. With the POF bundle irradiated, the amount of light output is shown in Fig. 3 (b). The light is transmitted through both the POF core and the adjacent POF core. Fig. 3 (b) shows the amount of light output decreases both on and besides the transit time Td-Ta.



(a) Expected light output with irradiating one POF

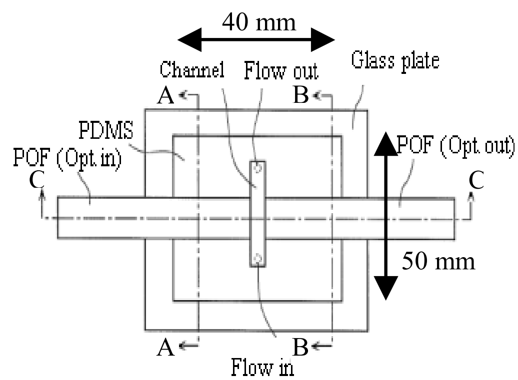


(b) Expected light output with irradiating POF bundle

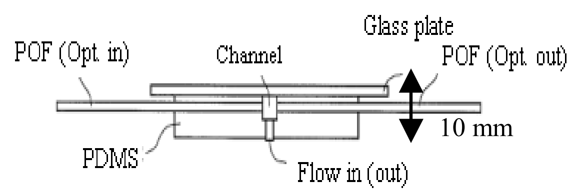
Fig. 3. Expected output model of a sensor

TABLE I
SENSOR SPECIFICATIONS

Chip size (W × D × H)	40 mm × 50 mm × 10 mm
Channel size (W × D)	300 μ m × 450 μ m
Particle size	100 μ m
POF Diameter	250 μ m
POF Core diameter	240 μ m
POF NA	0.5
POF number	10 pairs
Light source	Laser diode
Wavelength	650 nm



(a) Top view of a sensor



(b) Side view of a sensor

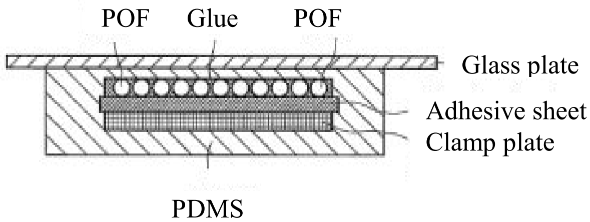
Fig. 4. Schematic diagram of a senor structure

III. SENSOR PROTOTYPE

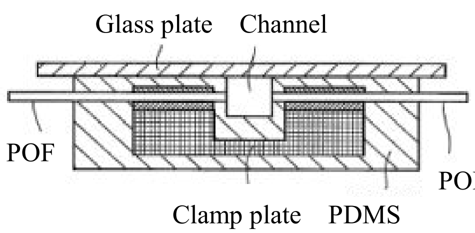
A. *Configuration of Sensor*

Table I shows specifications of the sensor. As POF has several advantages as mentioned above, we use POF as a transmission medium of the sensor. Assuming the sensor is implemented to automatic measurement system for cells such as cow egg cell in cloning process, we adopt POF with an outer diameter of 250 µm, a core diameter of 240 µm, and a numerical aperture of 0.5. Its core is made of polymethyl methacrylate. Its minimum bending radius as small as 5 mm makes the installation on the PDMS chip easier. With a 1 m long POF, the transmission-loss is as small as 0.15 dB at a wavelength of 650 nm.

Fig. 4 shows the structure of the sensor. A micro channel 300 µm wide and 450 µm deep is fabricated on the PDMS chip 40 mm wide, 50 mm long, and 10 mm high, and a sheet of POF is arranged across the micro channel. The PDMS chip is bonded to a glass slide, and the micro channel is connected to a pump with a microtube, thereby enabling particles to flow into the micro channel. Fig. 5 shows the cross section of the sensor: (a) cross section of POF and (b) cross section of the micro channel. POF is assembled exactly parallel with the optical axes coincide with each other. A light source placed at one side of the micro channel emits light onto the end of POF, and a detector placed at the opposite side of the micro channel receives light transmitted in the POF. A semiconductor red laser with a converging lens is used as a light source. With an optical detector employed, we detect particles by measuring changes in the amount of light output. The semiconductor red laser irradiates POF two ways: irradiate one POF and irradiate POF in a bundle. Fig. 6 is a photograph of the sensor.



(a) Cross section of POF (A-A, B-B)



(b) Cross section of a micro channel (C-C)

Fig. 5. Schematic diagram of cross section of a sensor

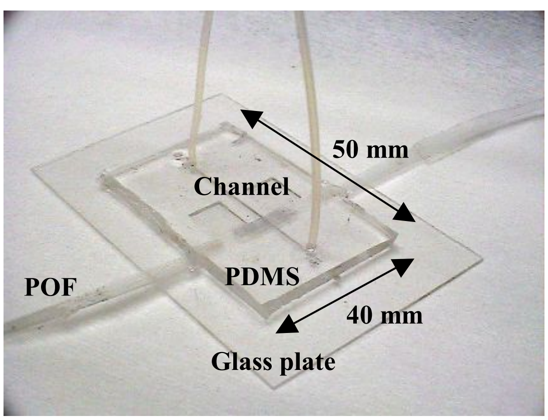


Fig. 6. Photograph of a sensor

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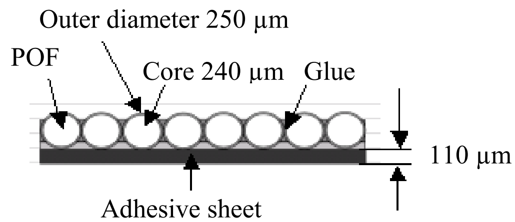
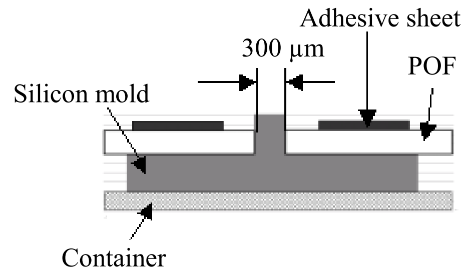
B. Fabrication of Sensor

The fabrication process of the sensor is shown in Fig. 7. POF (Mitsubishi Rayon ESCA CK10) were aligned under a microscope exactly parallel to each other with no space between them on the pressure sensitive adhesive sheet (Sumitomo 3M 879) 0.11 mm thick, and then bonded together with strong adhesive (Cemedine PPX). We cut apart the POF sheet with a sharp blade so that the end-face of POF had a sharp edge.

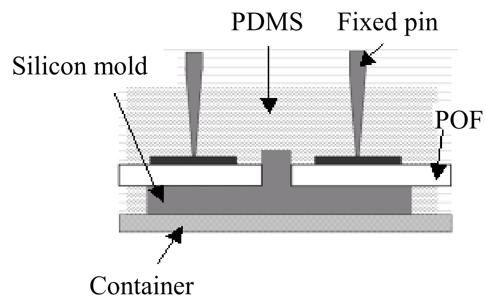
Utilizing the method of soft lithography, we fabricated a convex-shaped mold 300 μm wide and 450 μm deep for a micro channel with a silicon substrate, and then assembled the POF sheets on the mold. A resin plate 0.2 mm thick was used to couple the POF sheets 300 μm apart. Then the POF was impaled with a Φ0.5 mm pin on the xyz micro-positioning stage so that the optical axes coincided with each other. Fig. 8 shows a photograph of the POF aligned parallel to each other.



(a) POF aligned parallel to each other



(b) POF arranged on the mold of the silicon substrate



(c) PDMS mixed into the mold

Fig. 7. Fabrication process of a sensor

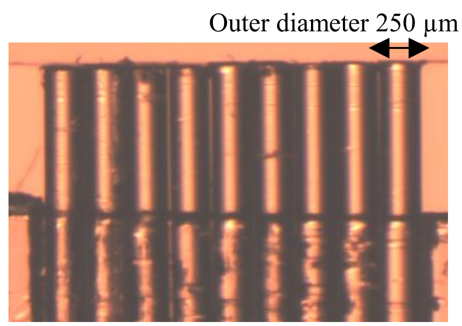


Fig. 8. Photograph of POF aligned parallel to each other

PDMS (Dow Corning Sylgard 184) was mixed into the mold enclosed in a container to cure at room temperature, which is within acceptable operating temperatures of POF. Then we carefully removed off the mold and pin.

A semiconductor red laser and an optical detector were placed across the micro channel. The micro channel was connected to a pump with a microtube (0.2 mm caliber and 0.4 mm outer diameter), through which particles are introduced into the micro channel. Fig. 9 is a photograph of the POF arranged on the silicon substrate.

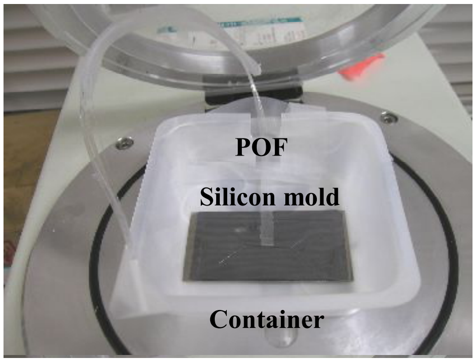


Fig. 9. Photograph of POF arranged on the silicon substrate

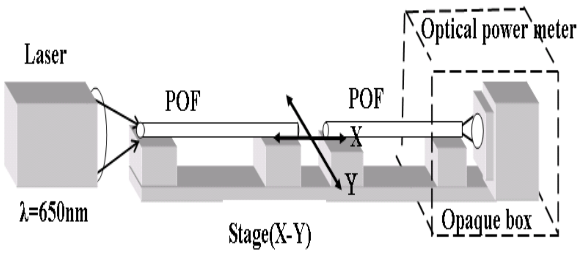


Fig. 10. Schematic diagram of a framework for POF evaluation

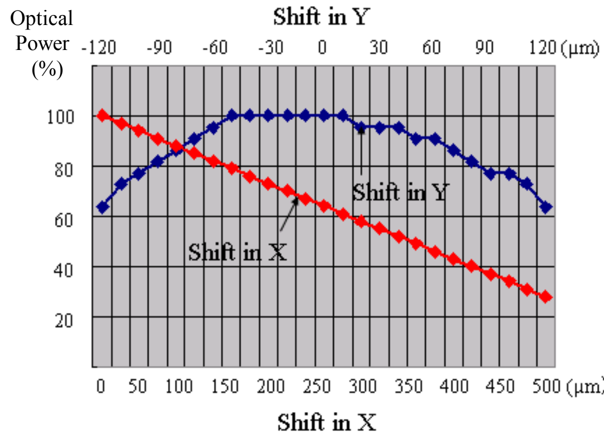


Fig. 11. The amount of light output in the horizontal (X) and vertical (Y) shift of POF

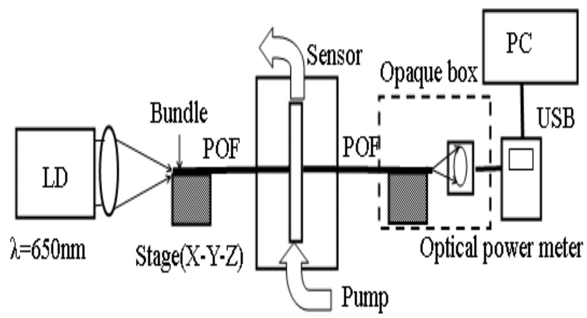


Fig. 12. Schematic diagram of experimental setup of a sensor

IV. EXPERIMENT

A. Evaluation of POF

We examined characteristics of POF used for the proposed sensor. Fig. 10 is a schematic diagram of a framework for POF evaluation. We placed two sheets of POF 300 μm apart from each other in a horizontal direction on the xy micro-positioning stage, while their optical axes coincide with each other. When the POF on the laser side changed its position ±120 μm in a vertical direction, the amount of light output was 60% less than that in previous position. The amount of light output was also measured with POF 0 μm-500 μm apart from each other in a horizontal direction. Fig. 11 shows the amount change of light output as POF moved in both horizontal and vertical directions.

B. Experimental setup

Fig. 12 shows the experimental setup of a sensor for validation. Fig. 13 is a photograph of the experimental setup. Since cow egg cell widely used in cloning is around 100 μm in a diameter, we used polystyrene beads with a diameter of 98 μm as a simulant particle. The particle in ethyl alcohol was pumped into the micro channel through the pump (Ismatec IPC-8) connected to the micro channel. A semiconductor red laser (Neoark DM-6535HB) with a wavelength of 650 nm, an output intensity of 18mW, and a numerical aperture of 0.45 was used as a light source. We connected POF to the laser in two ways, connecting one POF and connecting POF in a bundle, and irradiated POF in light beam < Φ1 mm. The micro channel was irradiated through the POF. We measured the amount of light output with an optical power meter (Hioki 3664) while blocking ambient light with an opaque box, and stored the acquired data in the personal computer every 0.2 second. A microscope equipped (Olympus SZX7) with IEEE1394 CCD camera (Point Grey Research) was connected to the personal computer so that the particle flowing was observed.

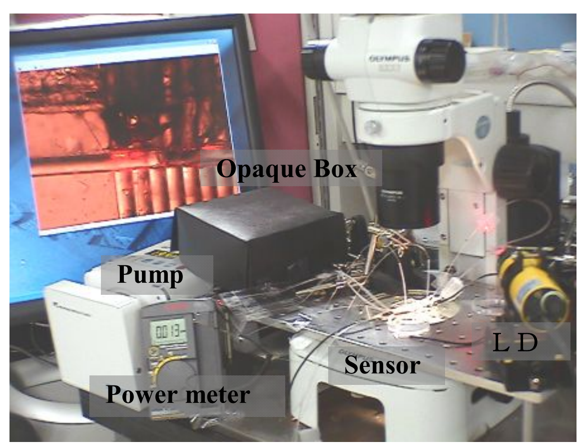
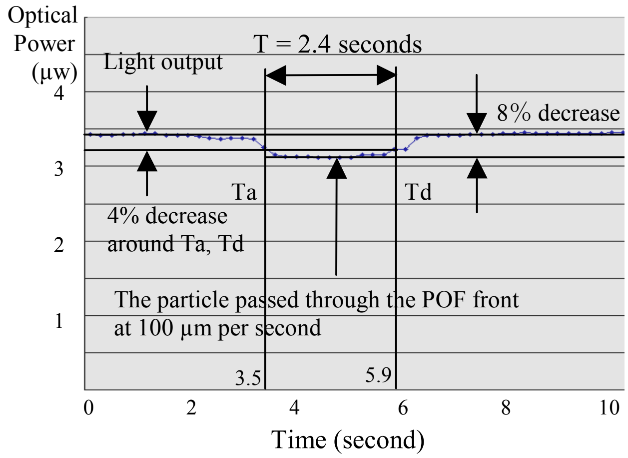
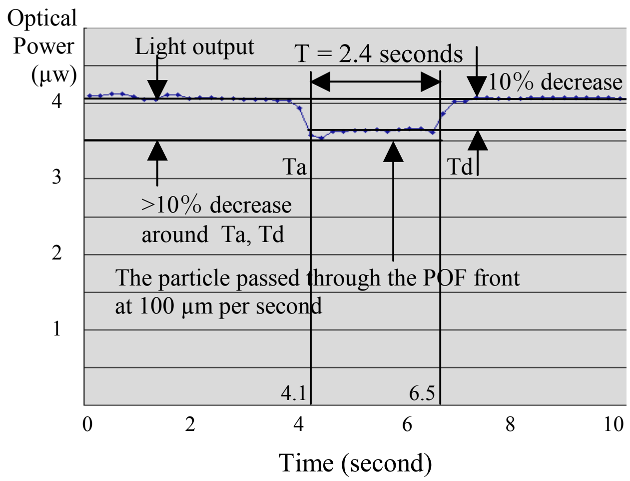


Fig. 13. Photograph of experimental setup



(a) Experimental measurements of light output with irradiating one POF



(b) Experimental measurements of light output with irradiating POF bundle

Fig. 14. Experimental measurement of a sensor

V. RESULTS AND DISCUSSION

In this section we provide experimental results for the proposed sensor. Using a particle with a diameter of 98 µm flowing 100 µm per second, we obtained the following experimental results. First, with the particle irradiated with the light emitted through one POF, we observed 8% decrease in the amount of light output when the particle passed through the POF front. We also observed the similar decrease in the adjacent POF output. When the particle passed through both the first 40 µm and the end 40 µm of the POF front, the adjacent POF output also decreased. Fig. 14 (a) shows the experimental results for light emitting through one POF.

Next, with the particle irradiated with the light emitted through the POF bundle, we observed 10% decrease in the amount of light output when the particle passed through the POF front. We also observed the similar decrease in the adjacent POF output. When the particle passed through both the first 40 µm and the end 40 µm of the POF front, the light output decreased greater than that through one POF, owing to the particle blocked the light from the adjacent POF. Fig. 14 (b) shows the experimental results for light emitting through the POF bundle.

With the optical power meter, we observed a decrease in light output approximately for 2.4 seconds. Watching a particle on the computer display connected to the microscope equipped with CCD camera, we confirmed that the power meter showed a decrease in light output when the particle passed through the POF front.

VI. CONCLUSION

In this paper, we proposed a sensor for detecting particles flowing in a micro channel fabricated with PDMS chip using POF array. We confirmed that particles in a micro channel were detected with the proposed sensor by measuring changes in the amount of light output. Since this sensor simultaneously detects plural particles with a diameter of around 100 µm flowing in a micro channel, it can be implemented in automatic measurement systems of cells in desktop bio plant, enabling to facilitate the automation of cloning procedures.

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